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The Propagation of the Electromagnetic Waves at Frequencies of the Russian Radio Navigation System RSDN-20 (Alpha) during a substorm at high latitude ionosphere

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Abstract

The work presents the results of the simulation of electromagnetic wave propagation with frequency corresponding to carrier in the network of transmitters of radio-technical system of long-distance navigation (RSDN-20) operating on the territory of Russia in the range of ultra-long waves. The numerical experiment was performed with ionospheric parameters corresponding to the magnetic substorm on 11.12.2015. These simulation results were obtained with using EISCAT incoherent scatter radar data on Svalbard and the Wait's two-parameter exponential profile for the D-region of the ionosphere.

1 Introduction

Ultra-long waves include electromagnetic very low frequency waves with frequencies of 3-30 kHz. This range is mainly used to transmit radio navigation signals and time signals. The Russian radio navigation system RSDN-20 (Alpha) system consists of four transmitters which are located in Novosibirsk (55°45′, 84°26′), Krasnodar (45°24′, 38°09′), Komsomolsk-on-Amur (50°04', 136°36′) and the Revda (68°02′, 34°40′) in Murmansk region. These transmitters broadcast 3.6 second signal sequences at 11905 Hz, 12649 Hz, and 14881 Hz frequencies [1, 2]. The variations in electron concentration and the height of the reflective layer determine the radio waves propagation in the VHF range. The presence of a response to changes in electron concentration in the D layer of the ionosphere and regularly operating sources of the radio signals make it possible to carry out geophysical investigations of the ionosphere by measuring the characteristics of received radio signals. The numerical experiment method allows to obtain reference characteristics of radio signals in different and fully controlled geophysical conditions.This is important for the further interpretation of the data.
The authors present the results of a series of numerical experiments on the propagation of navigation system RSDN-20 electromagnetic signals in the Earth-Ionosphere waveguide during conditions of the geomagnetic substorm in polar region.

2 The event 11 December 2015

The features of the VLF waves propagation at high latitude ionosphere during the charge particle precipitation into the ionosphere during a substorm was investigated. The polar substorm on 11 December 2015 (Figure 1) year was studied in detail in time interval 15.30-17.00 UT (evening sector, MLT=UT+3). The substorm was observed during the absence of the magnetic storm. The substorm amplitude reaches the value 1000 nT on HOR station of the IMAGE magnetometer network. The substorm leads to the abrupt increase of the ionosphere plasma density (more than order) at altitudes 100-100 km according to the EISCAT 42m radar data on Svalbard. It was quite strong ionosphere disturbance for this latitude because substorm for example leads to the strong growth of the GPS phase scintillations (more than 2 radians) [3] and gap in total electron content (TEC) variations according to the GPS receiver data on NYA station.

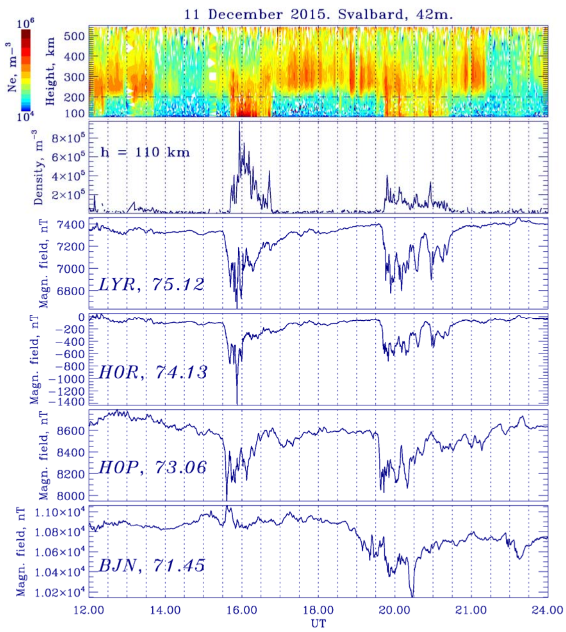

Figure 1. The variations of the ionosphere plasma density Ne with the altitude according to the EISCAT 42m radar data on Svalbard, variations of the Ne at altitude 110 km; variations of X-component of the geomagnetic field on LYR, HOR, HOP, BJN, after the station code the geomagnetic latitude is shown.

3 Environment conditions

Magnetic substorm on 11.12.2015 was selected as perturbed conditions for simulation. The calm conditions were taken half an hour before the sharp increase of the plasma density (determined by EISCAT radar) due to the particles precipitation into the polar regions of the Earth's ionosphere.
The ionosphere profiles used for modelling are derived from the EISCAT 42m radar data, interpolation techniques and Wait's two-parameter exponential profile [4]:

$$N_e(h) = 1.43 \cdot 10^7 e^{(-0.15h')} e^{[(\beta-0.15)(h-h')]}. \qquad (1)$$

where h' and β are in km and km^{-1}. The two parameters, h' and β, control the height of the profile and the sharpness of the ionospheric transition.
Figure 2 shows a series of profiles used in numerical experiments discussed below. The profile numbers are used in the discussion of the results obtained to identify the environment conditions used for the calculations.
In the presented numerical experiments magnetic field was accepted to the vertical, equal to $5.3 \cdot 10^{-5}$ T, directed to the Earth's surface.
The frequency of collisions with neutrals was calculated from the EISCAT data, the NRLMSISE2000 model data and the analytical approximation of the measurement results presented in [4]:

$$\nu_e(h) = 1.816 \cdot 10^{11} e^{(-0.15h)}. \qquad (2)$$

The conductivity profile of the lithosphere was approximated on the basis of the results of the conductivity studies on the Kola Peninsula of several scientific groups published in the paper [5].

4 Working space and source

As a working area for the numerical experiment, the authors used the uniform horizon section of the Earth-ionosphere waveguide. The horizontal size of the section was 128x400 km. Altitude in the atmosphere and ionosphere - 200 km, in depth in the lithosphere - 25 km. The grid step above the Earth's surface is 500 m, vertically in the lithosphere is 250 m. The center of the signal source was located at a distance of 64 km from the three side faces of the obtained parallelepiped. For all external faces except the lower one, the condition of free wave departure together with the adapted absorbing layers PML and Berenger's loss profile [6] was used as in the work [7].
A flat array of 60 km high and 60 km wide electric dipoles was used as the source. Source signal was the sum of harmonic oscillations at frequencies of radio-technical system of long-distance navigation (RSDN-20) 11905 Hz, 12679 Hz and 14881 Hz [1, 2].

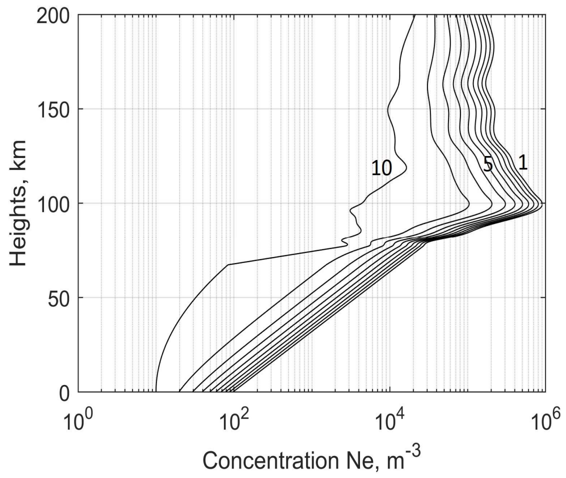

Figure 2. Electronic concentration profile series. From perturbed ionosphere conditions with marked digit 1 and corresponding substorm 11.12.2015 to calm conditions with marked digit 10.

5 Numerical scheme

The numerical scheme used to simulate electromagnetic wave propagation is developed by the authors. It is an original explicit scheme of splitting into spatial directions and physical processes with anti-flow approximation of spatial derivatives (Godunov's method with flow correction). This scheme is conservative, monotonic, has 2nd order of accuracy in time and 3rd in spatial variables [8]. The integration scheme of Maxwell's equations in [8] allows simulating the propagation of monochrome harmonic signals in magnetized ionospheric plasma. The structure of the proposed method in the consequence of splitting by physical processes allows to apply analytical methods for physical processes not related to spatial distribution of electromagnetic fields, as well as to easily change its individual blocks. Circuit blocks responsible for the processes of attenuation, oscillation and rotation under the action of the external magnetic field have been changed to allow modeling of broadband electromagnetic signals in the way specified in [9]

6 Results of experiments and discussion

Figures 3 and 4 shows the variations in the amplitudes of the main electromagnetic field components in percent at the Earth's surface level for different numerical experiments compared to the amplitudes of the field under calm conditions (Experiment 10). On the x axis, the graphs indicate the experiment number, and the color is the graphs for different frequencies from the set used by the RSDN-20 system. It can be clearly seen that the effect of the particles precipitation into the ionosphere of polar latitudes was distributed according to the increasing frequency of the signal.

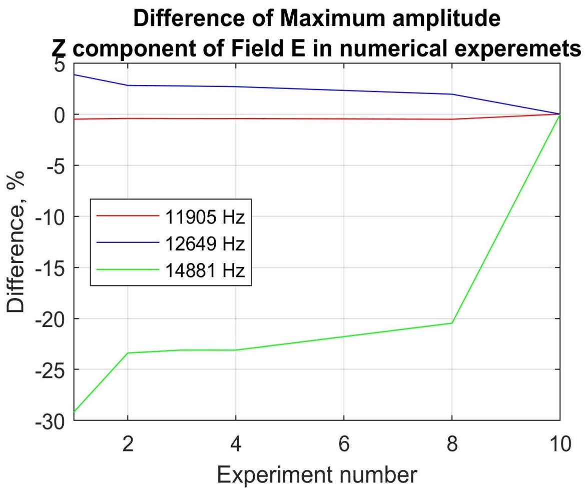

Figure 3. Amplitude changes of the E_z electromagnetic field component in percent at the Earth 's surface level for different numerical experiments compared to the amplitude under calm conditions (Experiment 10).On the x axis, the graphs indicate the experiment number, and the color is the graphs for different frequencies from the set used by the RSDN-20 system.

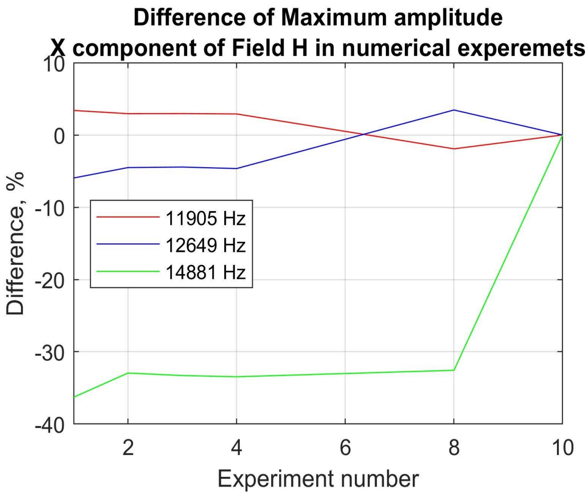

Figure 4. Amplitude changes of the H_x electromagnetic field component in percent at the Earth 's surface level for different numerical experiments compared to the amplitude under calm conditions (Experiment 10). On the x axis, the graphs indicate the experiment number, and the color is the graphs for different frequencies from the set used by the RSDN-20 system.

At the maximum frequency of the system RSDN-20 14881 Hz for almost all changed profiles of ionospheric parameters there is a decrease in amplitude of the main components of the electromagnetic field up to 30% under magnetic substorm conditions. These sufficiently significant changes in signal strength may well be recorded by instrumental methods on a network of ground-based VLF wave receiving points and further used to assume the state of the ionosphere on radio routes.

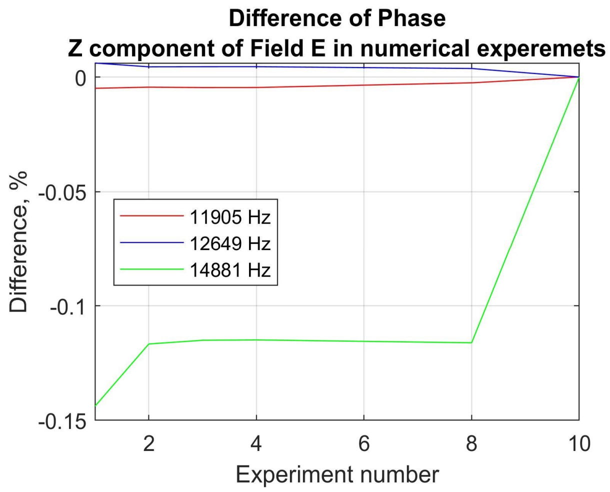

Figure 5. Phase changes of the E_z electromagnetic field component in percent at the Earth 's surface level for different numerical experiments compared to the phase under calm conditions (Experiment 10). On the x axis, the graphs indicate the experiment number, and the color is the graphs for different frequencies from the set used by the RSDN-20 system.

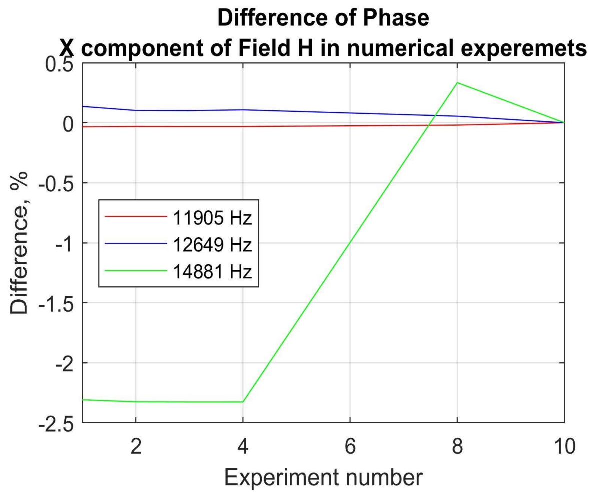

Figure 6. Phase changes of the $H_x$electromagnetic field component in percent at the Earth 's surface level for different numerical experiments compared to the phase under calm conditions(Experiment 10). On the x axis, the graphs indicate the experiment number, and the color is the graphs for different frequencies from the set used by the RSDN-20 system.

The other two frequencies are subject to much less amplitude distortion. For ionospheric parameter profiles used in this work, signal distortion does not exceed 10%, besides the nature of the distortion itself is more related to the shape of ionosphere parameter profiles than to the maximum concentration of electrons in the D region of the ionosphere. This will not allow the frequencies 11905 Hz and 12679 Hz to be used to investigate the state of the D layer by ground recording of navigation signals by a network of receiving VLF stations.

Figures 5 and 6 show the phase changes of the main electromagnetic field components in percent at the Earth's surface level for different numerical experiments compared to the phases of the field components under calm conditions. It can be seen that in all experiments for all frequencies of the RSDN-20 system the phase distortions did not exceed the 2.5%. This is good on the one hand for stable operation of the navigation system in difficult geophysical conditions, and on the other hand it does not allow any use of phase characteristics of navigation signals for geophysical research of the ionosphere.

7 Conclusions

Under the conditions of magnetic substorm on 11.12.2015, according to the obtained data of numerical experiments, there are significant, more than tens of percent, deviation of signal amplitudes at the level of the Earth's surface. At the same time the phase characteristics proved to be much more stable, their changes for different profiles of ionosphere parameters did not exceed 2.5%. Significant frequency dependence was observed in the disturbed ionosphere conditions. With increasing frequency, the amplitude distortion of the signals of the radio navigation system also increases in the case of disturbed ionosphere. At the maximum frequency of the system RSDN-20 14881 Hz there is a decrease in amplitude of the main components of the electromagnetic field up to 30% under magnetic substorm conditions.
The obtained results make it possible to conclude on possibility of using RSDN-20 signal at frequency 14881 Hz for geophysical research of ionosphere.

8 Acknowledgements

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9 References

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